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# Soil loss on the arable lands of the forest-steppe and steppe zones of European Russia and Siberia during the period of intensive agriculture

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ABSTRACT

An assessment of the total soil loss from cultivated land was undertaken for the Chernozems–Kastanozems belt of European Russia and Siberia, based on the results of the National Soil Survey for administrative regions and the detailed study of three sentinel catchments, located in different parts of the Russian Plain. The soil profile truncation method was used to assemble data on soil erosion for the period of intensive agriculture, which ranged in duration between 110 and 230 years for the different parts of the sentinel study catchments and which had mean durations of 50–220 years for the total area of arable land comprising the administrative regions of Russia. The average value of the mean annual erosion rate for all regions of European Russia was estimated at 0.5 mm $yr^{-1}$ for Chernozems and 0.4 mm $yr^{-1}$ for Kastanozems, equivalent to ~6 t $ha^{-1}$ $yr^{-1}$ and ~4.8 t $ha^{-1}$ $yr^{-1}$, respectively. The total volume of soil eroded on arable lands during the period of ploughing, in the Chernozems–Kastanozems soil belt of Russia, amounted to 33.4 × $10^9$ $m^3$ (excluding sediment re-deposition on the arable land). The topography of arable slopes and the erosion index of precipitation are the critical factors determining the differences in the rates of soil loss, both at the level of small catchments and at regional level, while the duration of the ploughing period does not significantly affect the proportion of eroded land. The contribution of wind erosion to soil loss of the study regions located in the dry steppe zone is identified. It was established that the values of soil erosion rates obtained using the soil profile truncation method are in good agreement with the evaluation of soil erosion rates compiled during long-term monitoring of soil loss using runoff plots. Our rates of soil loss do not agree with recent estimates based on the revised universal soil loss equation (RUSLE) for some administrative regions of European Russia with significant wind erosion.

## 1. Introduction

A distinctive feature of intensive agricultural development in Russia is its rather short duration, in contrast, for example, to Central and Western Europe. In many cases in Russia, this intensification spans no more than 2–2.5 centuries and for some regions of the steppe zone it is less than 50–100 years (Vodarskiy, 1988; Tsvetkov, 1957; Lyuri et al., 2010). The transformation of natural landscapes to agricultural zones caused widespread soil degradation, including soil erosion (Bazhenova et al., 1997; Litvin et al., 2003; Sidorchuk and Golosov, 2003). It is important to note, however, that even moderate rates of soil erosion lead to a reduction in soil fertility and agricultural production. A large expanse of such land is situated in the Russian Federation and it is therefore valuable to assess soil erosion rates quantitatively to evaluate the consequences of ploughing during the period of intensive agriculture (Krasilnikov et al., 2016). Here, it is necessary to underline the fact that the period after the collapse of the USSR in 1991 is characterized by serious land use and climate change, which both considerably influence erosion rates due to the abandonment of agricultural fields and a serious reduction of erosion associated specifically with snowmelt (Litvin et al., 2017; Golosov et al., 2018a, 2018b). In accordance with these controlling factors, the most serious reductions in erosion rates have been reported in the central and eastern parts of the forest-steppe and steppe zones of European Russia (Medvedev et al.,

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2016; Gusarov et al., 2018) and in Eastern Siberia (Ryzhov, 2015).

An understanding of the impact of erosion on soil productivity first appeared in Russia during the final third of the 19th C. The first scientific investigations of erosion processes (mostly related to gully and wind erosion) are documented by the works of Dokuchaev (1892), Massalsky (1897) and Kozmenko (1937). These early works and indeed, others, reported a dramatic picture of soil degradation and destruction across the steppe and forest-steppe zones. As a result, the State Survey of Erosion was established and several regional institutions were launched, which provided scientific support, erosion monitoring, and advice on the design of erosion control measures (Golosov and Belyaev, 2013).

Soil erosion monitoring at national scale is time consuming and expensive and is therefore rarely undertaken. More usually, evaluations of erosion rates for large territories are based on the application of erosion models (e.g., Ito, 2007; Van Oost et al., 2007; Sidorchuk et al, 2006; da Silva et al, 2011). Such models, however, have extensive data requirements due to their parameterization and generate soil erosion estimates with substantial uncertainty. An alternative approach involves calculations based on the soil profile truncation method, which uses the measured reduction in soil depth during the time period of interest (i.e., intensive soil cultivation in our case). This method has been applied in North America since the 1930s, when the USDA (United States Department of Agriculture) assembled both national and regional maps of soil erosion (USDA SCS, 1934). Here, it is noteworthy that this method of erosion rate evaluation is still included in USDA manuals (e.g., Ditzler et al., 2017). Nevertheless, the USDA turned to calculating soil losses using erosion models, such as USLE (Wischmeier and Smith, 1978) and its various modifications (USDA SCS, 1980).

In Europe, the soil profile truncation method has only been used at national scale in Iceland (Arnalds and Barkarsson, 2003). However, more widely, this method has been applied for the evaluation of soil loss in small catchments and for determination of soil loss for the entire period of cultivation (Houben, 2008; Rommens et al., 2005; Fuchs et al., 2011; Świtoniak, 2014; Smetanová et al., 2017). In Russia, the soil profile truncation method is used on all arable land for evaluating the impact of soil erosion on soil profile transformation. Here, for example, the results of field investigations have been published in State reports (Kulik et al., 2007), monographs (Sobolev, 1960), maps (Shoba, 2011), instruction manuals (Nosin et al., 1973) and numerous scientific papers (e.g., Ivanova et al., 1998; Kuznetsova et al., 2007). Therefore, despite the vast territory, the information on soil degradation due to soil erosion has been documented for the entire Russian Federation. Given the existence of such data, we assess soil loss at regional scale by combining strategic survey results with additional scientific data assembled by the authors, to evaluate both total soil loss and the intensity of soil erosion in key agricultural catchments during the period of intensive agricultural development (i.e., the past 110–230 years). More specifically, the main goal of our study was to evaluate total gross soil loss due to the combined influence of water and wind erosion, tillage erosion and root crop harvesting, for arable land in the Chernozems–Kastanozems belt of European Russia, Siberia and the Far East for different administrative regions for the period of intensive agriculture, ending at the beginning of the 1990s.

## 2. Materials and methods

### 2.1. Selection of the study area

Long-term agricultural development in the forests and the northern part of the forest-steppe zones of the East European Plain and Siberia from the Neolithic period was performed with primitive tools and agricultural systems. More intensive farming with the wooden ard plough began ~1000 years ago, accompanied by cut-burn and fallow agricultural systems. This land use regime, which existed in some regions of Russia until the 19th century, led to deforestation, arable cultivation and subsequent restoration following abandonment after several years of cropping (Sobolev, 1948; Tsvetkov, 1957). The detrimental consequences of erosion processes, which accompanied this farming system, were evidenced by washed-out soil matter (sediment), which was deposited in dry valley bottoms adjacent to the eroding arable lands.

The lands of the southern half of the forest-steppe and steppe zones of the East European Plain and Siberia were only occasionally used for cropping before the period of intensive land use, thereby being mostly natural pasture or virgin lands (Bazhenova et al., 1997; Ivanova et al., 1998; Goleusov and Lisetskii, 2008). The sedimentation rates in the local fluvial networks (dry valley bottoms) were thereby very low and erosion rates, recalculated on the basis of catchment areas, did not exceed 40 t $km^{-2}$ $yr^{-1}$ (Sidorchuk, 2018).

Intensive agricultural development began in the 15th C in the central part of European Russia (ER) (Sidorchuk and Golosov, 2003) and in the 16th C in the southern part of Siberia (Bazhenova et al., 1997). Territorial expansion during the 16th-20th C into the forest-steppe and steppe regions of ER and Siberia resulted in the conversion of virgin lands into arable fields and to an increase in the area of erosion prone land (Sobolev, 1948). This zone is mostly characterised by fertile soils, such as Chernozems and Kastanozems (Fig. 1), and so our study herein focused on this area.

It should be acknowledged that our estimates of the average annual erosion rates and total soil loss were calculated for the time period up to the beginning of the 1990s. This is due to the fact that after the collapse of the USSR in 1991, arable lands were abandoned in many areas due to economic problems (Lyuri et al., 2010; Golosov et al., 2018a; Ryzhov, 2015). Furthermore, in most of Russia, regular soil erosion surveys based on the use of the soil profile truncation method have not been carried out since the late 1980s, thereby providing a definitive time period for our data analysis.

### 2.2. Study sites

According to contemporary statistical surveys (Surinov et al., 2018), the territory of the Russian Federation is about 17.1 × $10^6$ $km^2$. The European part of Russia (EPR) lying west of the Urals, occupies ~23% of the total area; the Asian part of Russia (Siberia and Far East) accounts for ~77% of the area. The total area of land used for agricultural purposes in Russia is 4.0 × $10^6$ $km^2$ (23.5% of the total land area), including 1.94 × $10^6$ $km^2$ of arable land, of which only 0.54 × $10^6$ $km^2$ was sown in 2018 (Surinov et al.,2018). The arable lands are mostly located in a wide belt in EPR within the forest, forest-steppe and steppe zones, narrowing in Siberia and the Far East into the forest-steppe and steppe zones (Afonin et al., 2008). Podzols and Retisols underlie 21.5% of the arable lands, whilst 13.8% are on Haplic Luvisols and Greyzemic Phaeozems soils. The most fertile Chernozems and Kastanozems occupy 48.3% of the arable lands and Mollic Gleysols − 12.4%. The remaining 4% are classified as poor soils (Lithozems, Histosols, Solonetzes, etc.). More than 20% of the total arable area is prone to erosion by water and more than 8% to wind erosion (Volkov, 1988). Wind erosion has been identified on most parts of the arable land located in the steppe zone of ER (Larionov, 1993), and both Western and Eastern Siberia (Bazhenova et al., 1997).

The Chernozems–Kastanozems belt (Fig. 1) is the main region for growing agricultural crops in the EPR. On this basis, the assessment of soil loss within this agricultural belt is very important for sustainable development. A multiscale approach was used for the evaluation of the total gross soil loss from cultivated fields in the forest-steppe and steppe landscape zones of Russia, where the Chernozems–Kastanozems belt is located, for the period of intensive agriculture. Large scale assessments of erosion rates and total soil loss were undertaken for three sentinel catchments (Veduga creek, Maly Kolyshley River and Pogromka River; see Fig. 1) selected in different parts of the forest-steppe and steppe zones of EPR. These areas are documented to have experienced

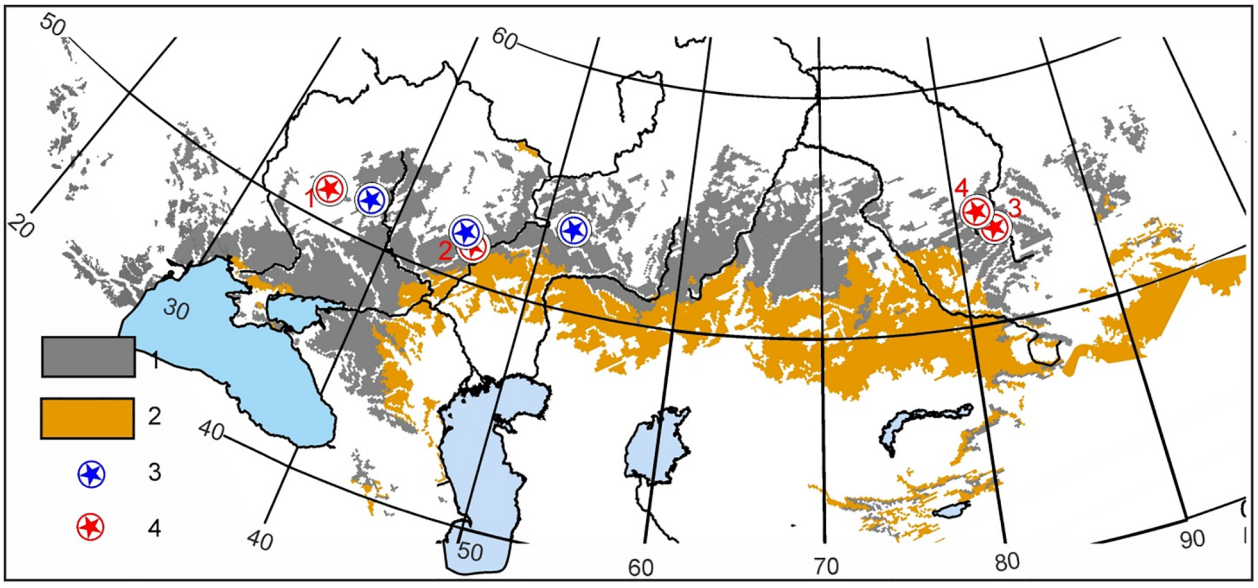


**Fig. 1.** The belt of 1 – Chernozems and 2 – Kastanozems across Northern Eurasia, compiled from the Soil Atlas of Europe (Akça et al., 2005) and Agroatlas (Afonin et al., 2008). Legend: 3 – the location of the sentinel study catchments (from west to east: Veduga creek, Maly Kolyshley River, Pogromka River); 4 – the locations of sites, described in Table 6 (1 – Chernigov Region, Ukraine, 2 – Saratov region, 3 – Novosibirsk region, 4 – Pre-Salair Plain).

**Table 1**
The location, main meteorological* characteristics and soil types of the three sentinel study catchments.

| Characteristics | Sentinel catchments | | |
|---|---|---|---|
| | Veduga | Maly Kolyshley | Pogromka |
| Co-ordinates | N 51.74° E 38.65° | N 51.93°E 45.32° | N 52.61° E 52.51° |
| Location | Srednerusskaya upland, Voronezh region | Privolzhskaya upland, Saratov region | Bugulmino-Belebeevskaya upland, Orenburg region |
| Landscape zone | Forest-steppe | Steppe | Dry steppe |
| Typical agricultural soil | Luvic Chernozems, Haplic Chernozems | Haplic Chernozems | Haplic Chernozems (Pachic) |
| Parent material | Calcareous loess-like loams | Eluvial-deluvial loams and clays | Deluvium-solifluction loams |
| Mean annual temperature (°C) for the time window 1946–2015 | 6.9 ± 0.4 | 5.2 ± 0.3 | 4.7 ± 0.3 |
| Mean temperature for three winter months (°C) for the time window1946–2015 | −5.6 ± 1.0 | −9.5 ± 0.9 | –11.5 ± 0.9 |
| Precipitation for the cold period (November–March) (mm) for time window 1960–2015 | 148 ± 23 | 153 ± 19 | 126 ± 14 |
| Precipitation for the warm period (April–October) (mm) for time window 1960–2015 | 412 ± 26 | 286 ± 25 | 244 ± 18 |

* Meteorological data were collected from the open-access internet resource supported by the All-Russia Research Institute of Hydrometeorological Information–World Data Centre (RIHMI-WDC) [www.meteo.ru].

different durations of intensive agriculture (Vodarskiy, 1988). All of these sentinel catchments are located within upland areas with more generally representative slope morphology and typical soils, climate and histories of intensive cultivation for the surrounding territory. Data for the trend of reduction in precipitation and mean air temperatures from the western to the eastern sentinel study catchments is presented in Table 1. Both erosion during spring snowmelt and rainstorms (warmer part of the year May–October) are observed within all three sentinel catchments. In contrast, wind erosion is not observed in these study areas, meaning that water erosion of soils is mechanistically dominant.

The sentinel study catchments are located within administrative regions with a high proportion of cultivated lands recorded during the 1980s (see Table S1).

## 3. Methods

The soil profile truncation method has been shown to be reasonably accurate in those areas with relatively uniform soil parent material and relatively flat terrain (plains and lowlands) and for soils with well-defined horizon boundaries, such as Chernozems and Kastanozems (Sobolev, 1948, Sobolev, 1960; Larionov, 1993). The soil profile truncation method (Sobolev, 1948; Lewis and Lepele, 1982; Volkov, 1988; Rommens et al., 2005; Świtoniak, 2014) was used to assemble data on soil erosion. Here, the depth of erosion/deposition is estimated using a comparison between the composition of a typical undisturbed soil profile and soil profiles on cultivated land with the same soil type and position on the slope.

The soil profile truncation method was used by regional Soil Investigation institutes in the State program to estimate the level of soil profile degradation due to erosion, following a methodology detailed in a consistent instruction manual elaborated for different soil types (Nosin et al., 1973). According to the classification of eroded soils (Nosin et al., 1973; Ditzler et al., 2017), soil, which had lost less than one third of the A + $B_1$ horizons, was classified as ‘slightly eroded’. Soils, which had lost one third – half of the A + $B_1$ horizons were

classified as 'moderately eroded', and in 'severely eroded soils', even the $B_1$ horizon had been ploughed due to the removal of overlying horizons and concomitant loss in soil depth. All cultivated fields around the country were regularly (over 15 years) investigated by digging soil pits and assembling descriptions of the soil profiles for evaluation of the erosion/deposition rates.

Accordingly, the mean annual soil loss/gain is determined using the following equation:

$$R = \frac{Mr - Ma}{T} = k\frac{Mr}{T} \quad (1)$$

where: $R$ = mean annual erosion/deposition rates, mm year$^{-1}$; $T$ = the duration of land cultivation, years; $M_r$ = the thickness of the A + AB + illuvial $B_1$ soil horizons at an undisturbed location, mm; $M_a$ = the thickness of soil horizons A + AB + $B_1$ on cultivated fields, mm, and; $k$ = a coefficient, which represents the eroded/depositional part of $M_r$.

All ploughed Chernozems and Kastanozems were divided by the regional soil research State authorities into five categories depending on the $k$ coefficient: non-eroded ($k = 0$); slightly eroded ($k \approx 0.23$); moderately eroded ($k \approx 0.42$); severely eroded ($k \approx 0.75$), and; depositional ($k < 0$). It is not possible to calculate total deposition within cultivated fields based on the results of the field surveys, because according to the instruction manuals, it wasn't stipulated that field surveys needed to determine the actual thickness of sediment accumulation.

Formula (1) was designed for soil erosion rate estimation for individual plots and fields. To calculate the mean rates of erosion ($R_{mean}$) for the group of fields, administrative region or district in question, the mean values of depth of erosion and duration of cultivation should be used. For any individual field, the depth of erosion $\Delta h$ (mm) is calculated as the product of erosion rate $R$ (mm yr$^{-1}$) and duration of cultivation $T$ (yr) according to the following equation:

$$\Delta h = RT \quad (2)$$

The mean depth of erosion $\Delta h_{mean}$ for the group of fields with variable durations of cultivation $T$ and erosion rates $R$ is calculated with the use of a probability density function $p_{TR}$ for these two variables:

$$\Delta h_{mean} = \int_0^{T_{max}} \int_0^{R_{max}} TRp_{TR}\,dR\,dT \quad (3)$$

The mean of the product of two independent variables is equal to the product of their means (Rohatgi, 1976; Pugachev, 1984). Therefore, for independent $R$ and $T$:

$$\Delta h_{mean} = \int_0^{h_{max}} \Delta h p_h\,dh = T_{mean}R_{mean} = \int_0^{T_{max}} Tp_T\,dT \int_0^{R_{max}} Rp_R\,dR \quad (4)$$

Here: $\Delta h_{mean}$ = mean depth of erosion, mm; $T_{mean}$ = mean duration of cultivation, years; and $R_{mean}$ = mean rate of erosion, mm yr$^{-1}$. These means are written using statistical representation with their probability density function $p_h$, $p_T$ and $p_R$ correspondingly. Therefore:

$$R_{mean} = \int_0^{R_{max}} Rp_R\,dR = \frac{\int_0^{h_{max}} \Delta h p_h\,dh}{\int_0^{T_{max}} Tp_T\,dT} \quad (5)$$

i.e. the average rate of erosion for any given group of fields $R_{mean}$ is equal to the average depth of erosion divided by the average duration of cultivation associated with intensive farming.

The probability density function for the duration of cultivation associated with intensive farming for the fields of a given territory ($p_T$) is known from land cadasters and agricultural yearbooks (Table S1). The probability density function for the depth of erosion $p_h$ is calculated from distributions of eroded soil types (i.e., coefficient $k$ in Eq. (1)) on a given territory and using an initial depth of soil horizon for virgin soil: $p_h = p(kM_r)$.

For the three sentinel catchments, we used detailed soil erosion maps at a scale of 1:10 000, based on the field soil-morphological survey prepared by the regional Soil Erosion Survey. The thickness of the soil horizons was determined for 80–90 soil pits (16–18 catena with 4–5 soil pits for the each catena) for the slopes of different configurations in each sentinel catchment for verification of soil erosion maps. The boundaries of each sub-catchment were defined on the topographic map and their areas were measured. The mean annual erosion rates were determined for each sub-catchment using the following equation:

$$R_m = \frac{\Delta h_{NE}F_{NE} + \Delta h_{SE}F_{SE} + \Delta h_{ME}F_{ME} + \Delta h_{SeE}F_{SeE}}{(F_{NE} + F_{SE} + F_{ME} + F_{SeE})T} \quad (6)$$

where: $\Delta h_{NE}$, $\Delta h_{SE}$,$\Delta h_{ME}$,$\Delta h_{SeE}$=erosion depth for non-eroded, slightly eroded, moderately eroded and severely eroded soils, respectively, mm; $F_{NE}$, $F_{SE}$, $F_{ME}$, $F_{SeE}$ = area of non-eroded, slightly eroded, moderately eroded and severely eroded soils respectively, ha; $T$ = the duration of land cultivation, years.

However, it is important to note that this method provides a basis for identifying the total reduction/increase in soil horizon depths $\Delta h = M_r - M_a$ due to the combined influence of different erosive processes (water, wind and tillage erosion and soil losses with root crop harvesting) for the entire period of agriculture. As mentioned above, the duration $T$ of intensive cultivation is well known for the fields of the forest-steppe and steppe landscape zones. Therefore, it is possible to estimate, quantitatively, soil loss for the period $T$ for individual fields or catchments using formula (6), as well as for administrative regions with formula (5), using statistical distributions of the values of both $\Delta h$ and $T$.

The mapping of soils within the Chernozems–Kastanozems belt with different levels of erosion was performed several times for the majority of farms (collectives or state) in the Soviet Union by regional soil research State authorities (Sobolev, 1948, Sobolev, 1960). The last soil survey for the whole of the Soviet Union is dated to the late 1980s (Volkov, 1988), which is representative for the period before significant changes in land ownership occurred in the Russian Federation. Soil loss characteristics in formula (5) ($\Delta h$ and its distribution $p_h$) are available from the soil erosion reports, based on the application of the soil profile truncation method (Volkov,1988) and the corresponding published results of regional soil surveys (The Combined State Register, 2014). The mean duration of the period of cultivation $T_{mean}$ was calculated using available statistical information (Tsvetkov, 1957; Vodarskiy, 1988) (see Supplemental SM1 and Table S1 for detail). The error of the soil loss calculations based on application of the soil truncation method is 15% (See Supplemental SM2 for details).

## 4. Results

### 4.1. Assessment of soil loss for individual sub-catchments within the sentinel study areas

#### 4.1.1. Pogromka River catchment

In total, 29 sub-catchments with a total area of 219 km$^2$ were investigated during field surveys in 1990 to estimate the erosion status of the territory within which ploughing started in the 19th C ($T \approx 110$ years of cultivation) (Supplemental Fig. S1 and Table S2). The soil map with the classification of soil erosion, prepared by the regional Soil Erosion Survey, was used for calculation of the areas $F$ of different types of eroded soils. The mean depth of the A + AB horizons in non-eroded soils was 57 cm. An average loss in soil depth of slightly eroded soils ($\Delta h_{SE}$), moderately eroded soils ($\Delta h_{ME}$) and severely eroded soils ($\Delta h_{SeE}$) was determined based on detailed description of soil pits at depths of 11 cm, 27 cm and 31 cm, respectively (see photos in SM3). Soils identified as being eroded, covered a total of 7078 ha (33% of the total area of cultivated land). The rates of erosion for individual sub-catchments varied from 0.05 to 1.72 mm yr$^{-1}$. The weighted mean erosion depth across the total area was 4.7 cm, equating to a mean erosion rate (Table 2) of 0.4 mm yr$^{-1}$ (~4.8 t ha$^{-1}$ yr$^{-1}$).

**Table 2**
Results of the evaluation of erosion rates for the cultivated soils of the Pogromka River sentinel study catchment.

| Soil erosion class | Area ($10^2$ ha) | Average loss in soil depth ($\Delta h$), cm | Erosion rate (mm $yr^{-1}$) |
|---|---|---|---|
| Non-eroded | 148.50 | 0 | 0 |
| Slightly eroded | 55.12 | 11 | 1 |
| Moderately eroded | 14.59 | 27 | 2.5 |
| Severely eroded | 1.06 | 31 | 2.8 |
| Total eroded soil | 70.77 | 14.6 | 1.3 |
| Total cultivated soil | 219.27 | 4.7 | 0.4 |

#### 4.1.2. Maly Kolyshley River catchment

More than 70 small sub-catchments with a total area of 107.2 $km^2$ were investigated in 1988 to estimate the erosion status of the territory with ploughing beginning in the 18th C (230 years of cultivation, according to the map at the beginning of the 19th C) (Supplemental Fig. S2, Table S3). The mean depth of the A + AB soil horizons for non-eroded soils in the Maly Kolyshley sentinel site was 65 cm. The average loss in soil depth of slightly eroded soils ($\Delta h_{SE}$), moderately eroded soils ($\Delta h_{ME}$) and severely eroded soils ($\Delta h_{SeE}$) was equal to 17 cm, 33 cm and 48 cm, respectively. Soils classified as eroded, covered an area of 8263 ha (77% of the total cultivated area). The mean erosion rate for the entire cultivated area is high; 0.65 mm $yr^{-1}$ or about 7.7 t $ha^{-1}$ $yr^{-1}$ (Table 3).

#### 4.1.3. Veduga Creek catchment

More than 50 sub-catchments were investigated in 1986 to estimate the erosion status of the cultivated fields in the Veduga Creek catchment (Supplemental Fig. S3, Table S4). Two main groups of fields were distinguished: 1) 1612 ha with ploughing beginning from the middle of the 18th C for about 230 years, according to a map dated to the year 1775, and; 2) 3297 ha with ploughing beginning from the middle of the 19th C, according to a map dated to the year 1840 (c. 130 years of cultivation). More than 150 patches of eroded soils were identified. The mean depth of the A + AB soil horizons for non-eroded soils in the Veduga sentinel site was 65 cm. Average loss in soil depths for slightly eroded soils ($\Delta h_{SE}$) and moderately eroded soils ($\Delta h_{ME}$) were equal to 18 cm, and 34 cm, respectively (See photos SM3). Soils classified as eroded in the first group of fields (Table 4), covered 385 ha (24% of the total area of cultivation), and in the second group of fields 617 ha (19% of the total area of cultivation).

The mean annual soil erosion rates for the arable land with different periods of cultivation are almost equal (Table 4). This is due to the effect of a high proportion of the fields classified as non-eroded and of a lower proportion of moderately eroded soils in the second group. If mean erosion rate is calculated only for eroded soils, the mean rate was estimated at 1.15 mm $yr^{-1}$ (≈14 t $ha^{-1}$ $yr^{-1}$) for the first group of fields and 1.52 mm $yr^{-1}$ (≈18 t $ha^{-1}$ $yr^{-1}$) for the second group of fields. Assuming this erosion rate for the last 130 years is valid for the first group of fields, the rate of erosion for the first 100 years (from the mid-18th C to the mid-19th C) would be ~0.67 mm $yr^{-1}$ (≈8 t $ha^{-1}$ $yr^{-1}$).

**Table 3**
Results of the evaluation of erosion rates for the cultivated soils of the Maly Kolyshley River sentinel study catchment.

| Soil erosion class | Area ($10^2$ ha) | Average loss in soil depth ($\Delta h$), cm | Erosion rate (mm $yr^{-1}$) |
|---|---|---|---|
| Non-eroded | 24.57 | 0 | 0 |
| Slightly eroded | 72.76 | 17 | 0.75 |
| Moderately eroded | 9.09 | 33 | 1.43 |
| Severely eroded | 0.78 | 48 | 2.1 |
| Total eroded soil | 82.63 | 19.1 | 0.83 |
| Total cultivated soil | 107.20 | 14.7 | 0.65 |

The rate of erosion on eroded soils is more than twofold that on the fields of the second group (last 130 years of cultivation), compared with those on the fields of the first group (taking the first 100 years of cultivation). It is likely that erosion rates had increased after the start of tractor and other agricultural machinery use. Firstly, this led to soil compaction, especially in the 1970s, when the heaviest machinery was used for different types of field operations on the arable fields. As such, surface runoff and soil erosion increased (van Oost et al., 2005). Secondly, tillage erosion rates and soil loss during the harvesting of root crops became higher after World War II due to more frequent soil cultivation and changes in crop rotations in favour of root crops.

### 4.2. Mean soil losses for the administrative regions within the Chernozems–Kastanozems belt of Russia

Fig. 2 and Table 5 present the estimated mean annual soil losses for the period of cultivation for the 29 administrative regions of Russia located within the forest-steppe and steppe zones dominated by Chernozems and Kastanozems.

The total area of the 17 regions within the EPR dominated by Chernozems and Kastanozems is 116.6 × $10^6$ ha, with 62.9 × $10^6$ ha of arable land, of which 44.1 × $10^6$ ha are covered by Chernozems and 8.3 × $10^6$ ha by Kastanozems. On the basis of our estimates, non-eroded soils cover 74.5%, slightly eroded Chernozems/Kastanozems with an average depth of erosion 19/14 cm – 20.7%, moderately eroded soils with an average erosion depth of 33/25 cm – 4.3% and, severely eroded soils with an average erosion depth of 59/45 cm – only 0.5%. The estimated total volume of soil loss was 28.3 × $10^9$ $m^3$ and the overall average erosion depth was 5.4 cm. This total volume of erosion was distributed among fields with the above mentioned classes of eroded soils in the descending order: 70% (19.8 × $10^9$ $m^3$) – slightly eroded; 25% (7.1 × $10^9$ $m^3$) – moderately eroded, and 5% (1.4 × $10^9$ $m^3$) – severely eroded (see Supplemental Table S5 for details).

The average value of the mean annual erosion rate for all regions of EPR was estimated at 0.5 mm $yr^{-1}$ for Chernozems and 0.4 mm $yr^{-1}$ for Kastanozems (Table 5), equivalent to ~6 t $ha^{-1}$ $yr^{-1}$ and ~4.8 t $ha^{-1}$ $yr^{-1}$, respectively. This value is in a good agreement with recent assessments of erosion rates in EPR, based on erosion model calculations (Litvin et al., 2017; Golosov et al., 2018a).

The average rate of soil erosion for regions with Chernozems was found to correlate most strongly with relief, with the minimum erosion value (0.11–0,18 mm $yr^{-1}$) estimated for the Tambov and Lipetsk regions, which are located within the Oksko-Donskaya lowland (see Supplemental Fig. S4 for location). One of the highest values (0.7 mm $yr^{-1}$) was estimated for Bashkiraya, where arable land is located within the Bugulmino-Belebeevskaya upland and also for the foothills of the Ural mountains and the Saratov region (0.83 mm $yr^{-1}$), the western part of which is located in the most dissected section of the Privolzskaya upland. The rainfall erosivity index was identified as the second key factor, as evidenced by the high erosion rates estimated for the Rostov, Stavropol and Belgorod regions, where relatively high values of the *LS* factor are combined with the frequent recurrence of heavy rainstorms (> 20 mm per rainstorm with a duration < 1 h) (Larionov, 1993; Panagos et al., 2017; Golosov et al., 2018a). It is likely that contribution of wind erosion to the total soil losses is considerable in the southern regions of EPR, located in the dry steppe (i.e., Rostov, Stavropol, Volgograd). Wind erosion reached 55–126 t $ha^{-1}$ $yr^{-1}$ in some locations in the abovementioned regions according to field assessments (Larionov et al., 1997).

Arable land occupies 33.8 × $10^6$ ha of the 533.9 × $10^6$ ha of area with Chernozems and Kastanozems in the 12 regions of Siberia and the Far East (Table 5). The total volume of soil loss due to erosion was estimated at 5.0 × $10^9$ $m^3$, with the corresponding average depth of soil loss estimated at 1.5 cm. This volume of eroded sediment was distributed among the fields with slightly, moderately and severely eroded soils as follows: 3.1 × $10^9$ $m^3$ (61%), 1.6 × $10^9$ $m^3$ (30.4%) and

**Table 4**
Results of the evaluation of erosion rates for the cultivated soils of the Veduga Creek sentinel study catchment with different ploughing periods.

| Soil erosion class | Duration of ploughing period | | | | | |
|---|---|---|---|---|---|---|
| | 230 years | | | 130 years | | |
| | Area ($10^2$ ha) | $\Delta h$, cm | Erosion rate (mm $yr^{-1}$) | Area ($10^2$ ha) | $\Delta h$, cm | Erosion rate, (mm $yr^{-1}$) |
| Non-eroded | 12.27 | 0 | 0 | 26.60 | 0 | 0 |
| Slightly eroded | 1.84 | 18 | 0.8 | 5.49 | 18 | 1.4 |
| Moderately eroded | 2.01 | 34 | 1.5 | 0.68 | 32 | 2.5 |
| Total (only eroded soils) | 3.85 | 26.4 | 1.15 | 6.17 | 19.5 | 1.5 |
| Total cultivated soil | 16.12 | 6.3 | 0.27 | 32.97 | 3.7 | 0.28 |

$0.44 \times 10^9$ $m^3$ (8.6%), respectively. In these regions, the average rate of soil erosion is also mainly associated with local relief characteristics and the recurrence of heavy rainstorms, with the minimum value in the Kurgan and Chelyabinsk regions (0.02–0.03 mm $yr^{-1}$) and the maximum in Primorsky province (0.6 mm $yr^{-1}$). The overall average value for all regions was estimated at 0.2 mm $yr^{-1}$ (Table 5, Fig. 2).

The greater prevalence of low values of soil loss in Siberia and the Far East regions is mainly explained by the relatively gentle slopes of cultivated lands in most regions. However, both water and wind erosion are observed in several regions, which are characterized by the relatively higher erosion rates (i.e., Altay, Irkutsk, Chita, Buryatiya). In other regions (i.e., Kemerovo), relief is the key driver for higher soil losses (Bazhenova et al., 1997; Khmelev and Tanasienko, 2009).

## 5. Discussion

The estimated average annual soil losses over the entire ploughing period at the three sentinel study catchments were found not to depend on the duration of land use under arable cultivation nor the total precipitation. On the contrary, the minimum values of annual soil loss were estimated for the Veduga catchment (Table 4), which is located in the region with the highest rainfall among the three sentinel catchments (Table 1). The main controls that determine total soil loss are associated with differences in the topography of the arable slopes. More specifically, the density of hollows was found to be the key factor controlling the estimated total soil losses, which are highest in the Kolyshley catchment followed by the Pogromka and Veduga catchments (Gusarov et al., 2018; Bezukhov and Entin, 2019). It has been shown, that ephemeral gullies are often formed along the hollow bottoms, and the sides of the hollows are subject to the most significant tillage erosion. The high density of the hollow networks on the arable land contributes to the export of a significant amount of soil due to the combined effect of tillage erosion, as a result of which, the soil moves during each field operation to the bottoms of the hollows.

Similar studies have previously been undertaken in different parts of Siberia. It was found, for example, that soil profiles were reduced in depth by 9 cm on average in the A horizon on the arable slopes of the Pre-Salair plain (Fig. 1; N 53.93° E 82.52°) over 120 years of cultivation with associated soil erosion (Khmelev and Tanasienko, 2009). Erosion depths in the Suzunsky and the Iskitim rayons were evaluated at 8.1 cm and 11.7 cm, respectively, based on the soil profile truncation method. The mean annual soil loss rates were estimated at 0.75 mm $yr^{-1}$ on the arable lands of the Pre-Salair Plain (Table 6). The total soil losses on the arable slopes of the Priobskoe plateau for the entire period of cultivation is about the same (8.4 cm), but the extent of eroded soils here is 3 times less than on the Pre-Salair plain. In the Irkutsk district (Irkutsk region), the thickness of the A horizon in eroded Luvic Greyzemic Phaeozems has been reduced by 5–10 cm, according to Kolesnichenko (2003). Reimche (1986) found that the thickness of the A horizon of Chernozems and Luvic Greyzemic Phaeozems had been reduced by 4.2–15.7 cm on arable lands with inclinations of 3–9° when compared with virgin soils in Buryatia.

Table 6 provides a comparison of soil erosion rates on arable land using different research methods. Here, it should be noted that there are very limited long-term data covering both the spring snowmelt and rainstorm seasons. The comparison reveals generally comparable estimates for soil erosion. In making this comparison, it should be borne in mind that the erosion estimates based on the soil truncation method also incorporate the impacts of tillage erosion and root crop harvesting.

Comparison of the results for estimates of the total soil loss for the administrative regions of EPR based on the use of the soil profile truncation method and on the basis of the USLE model is presented in Table 7. There is no correlation between the erosion assessments provided by the two independent methods, if the entire data point cloud is used for analysis (Fig. 3), because total erosion losses for the seven regions (circles), based on the soil profile truncation method are much higher than those generated by the USLE model. The impacts of wind erosion most likely influenced the estimates of total soil loss from arable land using the truncation method in the case of the southern regions (i.e., Rostov, Volgograd) and partly south-eastern regions (i.e., Saratov, Samara, Bashkiria and Orenburg) (see Table 7). All of the above mentioned regions belong to areas with documented wind erosion according to the Map of Soil Erosion, produced by the Dokuchaev Soil Institute (Stolbovoi and Fischer, 1998). Wind erosion is especially strong here in the spring during dry years, and this coincides with the period when the soils are ploughed over large areas and are not protected by crops (Larionov, 1993; Larionov et al., 1997). In the case of the western part of

the Saratov, Samara and Uliyanovsk regions, located in the Privozhskaya Upland region and the Bashkiria and Orenburg region, which are occupied by the Bugulmino-Belebeevskaya upland (see Supplemental Fig. S4 for locations) and foothills of the Ural mountains, the other reason for the differences in the estimates of total loss is associated with a dense network of hollows on the arable land. Ephemeral gullies are formed in the bottoms of these hollows during surface runoff and their contribution to total soil losses can seriously exceed the total soil losses due to sheet and rill erosion (Vandaele and Poesen, 1996). But, ephemeral gully erosion is not taken into account when calculating soil losses using the USLE model (Wischmeier and Smith, 1978). A relatively good correlation between the assessments of mean annual soil erosion rates using both the USLE model and the soil truncation method was found for the remainder of regions (Fig. 3).

It should be noted that our estimated values of mean annual gross erosion rates (excluding sediment accumulation inside the arable fields) are comparable in magnitude with the estimates obtained for the Great Plains of North America (Beach, 1994; Trimble, 1999). These territories are also characterized by a relatively short history of agricultural development. At the same time, the mean annual erosion rates for the entire period of agricultural development, calculated for the loess belt of Western and Central Europe, are somewhat lower (van Hooff and Jungerius, 1984; Rommens et al., 2005). However, there is an increase in erosion rates with a reduction in the period of agricultural development to less than 1000 years (Bork, 1983). Here, it can be assumed that such a trend is due to two reasons. Firstly, the reliability of

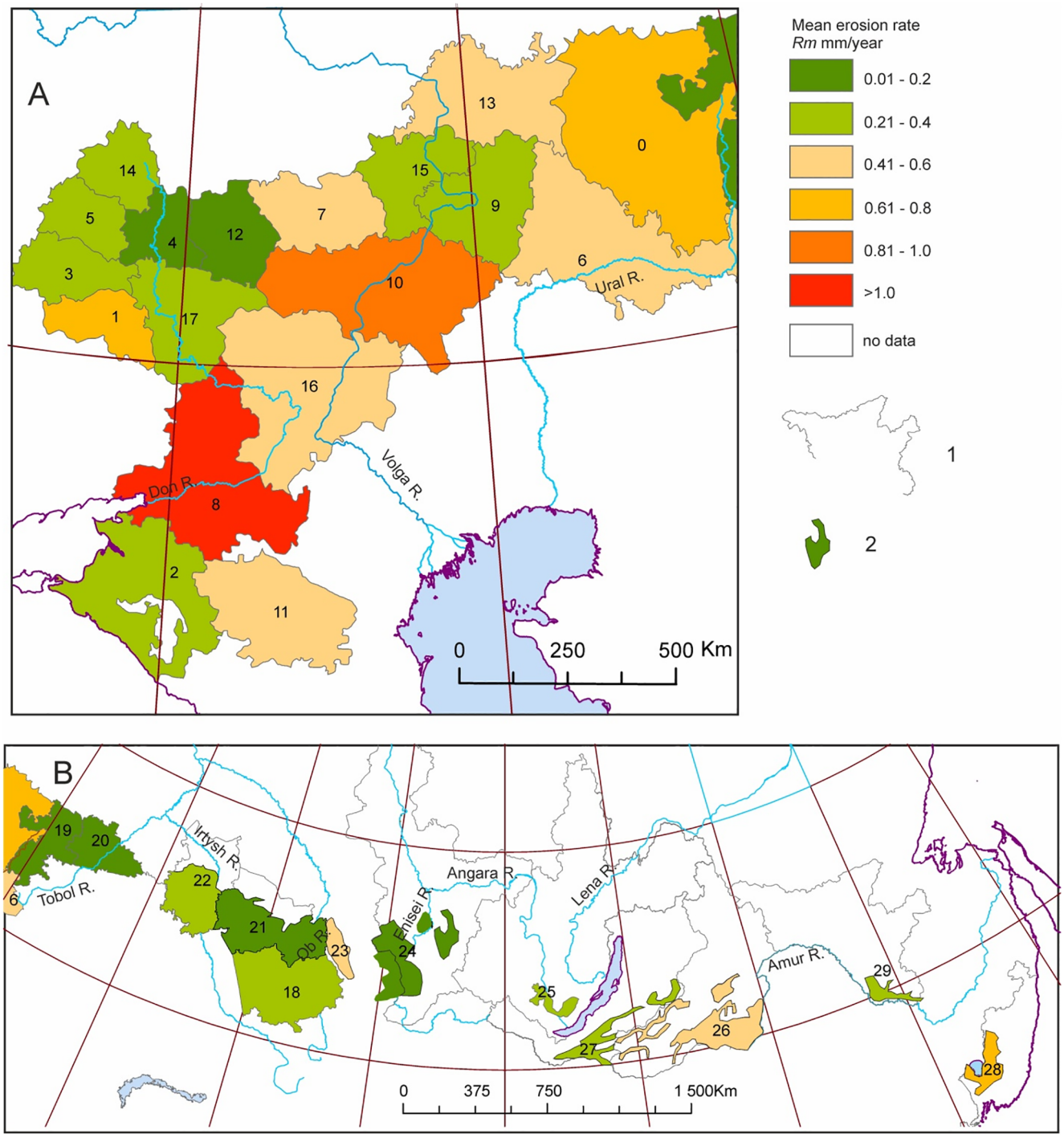


**Fig. 2.** Mean soil loss rate $R$ (mm $yr^{-1}$) for the period of intensive agriculture across 29 administrative regions (the numbers signify the administrative region, see Table 5 for information concerning the names of the regions) of European Russia (A) and Siberia and the Far East (B). Legend: $R$, mm $yr^{-1}$ – the mean annual rate of soil loss for the period of intensive agriculture for the administrative region; 1 – boundary of region; 2 – area of the arable lands within regions of Siberia and Far East.

determining the total period of agricultural development decreases as its duration increases, and often for long time periods (over 1000 years) there is a significant overestimation of the duration of ploughing (Dotterweich, 2008; Smetanová et al., 2017). Secondly, the period of tillage and harvesting using tractors and other agricultural machinery is characterized by an increase in the erosion rate due to soil compaction (Morgan, 1996). Since mechanization and more intensive cropping systems were introduced during the 20th C, tillage erosion has become more important (Van Oost et al., 2005). As a result, the gross erosion rates are much higher for areas with relatively short periods of intensive cultivation (Chernozems–Kastanozems belt in Russia, Great Plain in USA).

Generally speaking, our estimates of soil loss exceed contemporary soil losses reported for most parts of Western and Central Europe, but are lower than those estimated for some countries in Southern Europe with hilly landscapes (Panagos et al., 2015). The estimated rate of soil loss is much higher for the arable land area with eroded soils, which equates to about 20% of the total area of arable land. The variability of soil losses between our regions is rather high: $C_v$ representing the standard deviation/mean is 0.56 for EPR and 0.76 for Siberia and the

**Table 5**
Summary data for soil erosion estimates for the period of intensive agriculture for cultivated land within the administrative regions of European Russia and Siberia/Far East, located within the Chernozems–Kastanozems belt. Key: N – region shown on Fig. 2; E – area of eroded soil on the arable land; T – mean duration of ploughing, years; Rm – mean gross rate of erosion (mm $yr^{-1}$).

| N | Region | Area $10^3$ ha | | | Depth of erosion, m | | Volume of erosion, $10^9$ $m^3$ | T, yr | Rm mm $yr^{-1}$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | Arable land | E | Eroded soils | Arable land | | | Eroded soils | Arable land |
| | | | | | *European part of Russia, Chernozems* | | | | | |
| 0 | Bashkiriya | 14,295 | 1514.8 | 532.97 | 0.17 | 0.060 | 0.91 | 85 | 2.02 | 0.71 |
| 1 | Belgorod | 2713.4 | 1651.8 | 671.6 | 0.26 | 0.105 | 1.81 | 165 | 1.64 | 0.67 |
| 2 | Krasnodar | 8327.7 | 4227.3 | 470.7 | 0.27 | 0.030 | 1.41 | 100 | 3.00 | 0.33 |
| 3 | Kursk | 2999.7 | 1456.8 | 329.45 | 0.22 | 0.050 | 0.74 | 160 | 1.40 | 0.32 |
| 4 | Lipetsk | 2407.7 | 1647.1 | 202.8 | 0.22 | 0.027 | 0.46 | 150 | 1.50 | 0.19 |
| 5 | Orel | 2465.2 | 700.44 | 151.54 | 0.24 | 0.052 | 0.37 | 180 | 1.35 | 0.29 |
| 6 | Orenburg | 12,370 | 5432 | 1447.5 | 0.23 | 0.062 | 3.32 | 120 | 1.91 | 0.51 |
| 7 | Penza | 4335 | 1708.6 | 358.49 | 0.27 | 0.056 | 0.98 | 140 | 1.95 | 0.41 |
| 8 | Rostov | 10,097 | 4834.1 | 1524.7 | 0.26 | 0.082 | 4.03 | 75 | 3.52 | 1.11 |
| 9 | Samara | 5359.5 | 2264.5 | 564.12 | 0.19 | 0.047 | 1.06 | 120 | 1.56 | 0.39 |
| 10 | Saratov | 10,124 | 6358.7 | 2961.6 | 0.20 | 0.091 | 5.79 | 110 | 1.78 | 0.83 |
| 11 | Stavropol | 8043.7 | 2001.4 | 280.45 | 0.27 | 0.037 | 0.77 | 50 | 5.51 | 0.77 |
| 12 | Tambov | 3446 | 2256.3 | 166 | 0.20 | 0.015 | 0.33 | 140 | 1.44 | 0.11 |
| 13 | Tatarstan | 6783.7 | 1199.8 | 374.37 | 0.18 | 0.056 | 0.64 | 120 | 1.43 | 0.45 |
| 14 | Tula | 2567.9 | 746.43 | 181.68 | 0.19 | 0.046 | 0.35 | 220 | 0.88 | 0.21 |
| 15 | Uliyanovsk | 3718.3 | 1113.7 | 284.9 | 0.15 | 0.039 | 0.44 | 140 | 1.09 | 0.28 |
| 16 | Volgograd | 11,294 | 1891.1 | 445.84 | 0.18 | 0.043 | 0.82 | 80 | 2.29 | 0.54 |
| 17 | Voronezh | 5221.6 | 3159.1 | 555.9 | 0.20 | 0.036 | 1.12 | 160 | 1.26 | 0.22 |
| | Total | 116,569 | 44,164 | 11,505 | | | 25.34 | | | |
| | Mean | | | | 0.22 | 0.057 | | 115 | 1.92 | 0.50 |
| | | | | | *European part of Russia. Kastanozems* | | | | | |
| 6 | Orenburg | 12,370 | 855.03 | 227.84 | 0.14 | 0.037 | 0.32 | 120 | 1.16 | 0.31 |
| 8 | Rostov | 10,100 | 1208.5 | 381.18 | 0.20 | 0.062 | 0.75 | 75 | 2.64 | 0.83 |
| 11 | Stavropol | 8044 | 2256.8 | 316.25 | 0.14 | 0.020 | 0.46 | 50 | 2.90 | 0.41 |
| 16 | Volgograd | 11,294 | 3985.8 | 939.68 | 0.15 | 0.036 | 1.43 | 80 | 1.91 | 0.45 |
| | Total | 41,804 | 8306.2 | 1865 | | | 2.97 | | | |
| | Mean | | | | 0.16 | 0.036 | | 90 | 1.77 | 0.40 |
| | | | | | *Siberia and Far East. Chernozems and Kastanozems* | | | | | |
| 18 | Altay | 25,090 | 7254.9 | 1030.1 | 0.16 | 0.023 | 1.65 | 85 | 1.90 | 0.27 |
| 19 | Chelyabinsk | 8852.9 | 3165.5 | 21.7 | 0.20 | 0.001 | 0.04 | 75 | 2.62 | 0.02 |
| 20 | Kurgan | 7148.8 | 1816.4 | 27.24 | 0.17 | 0.003 | 0.05 | 75 | 2.31 | 0.03 |
| 21 | Novosibirsk | 17,776 | 3925.7 | 202.5 | 0.15 | 0.008 | 0.31 | 95 | 1.62 | 0.08 |
| 22 | Omsk | 14,119 | 4371.9 | 200.8 | 0.19 | 0.009 | 0.38 | 75 | 2.51 | 0.12 |
| 23 | Kemerovo | 9565 | 1557.2 | 285 | 0.20 | 0.036 | 0.56 | 75 | 2.62 | 0.48 |
| 24 | Krasnoyarsk | 242,837 | 4003.3 | 202.9 | 0.16 | 0.008 | 0.33 | 70 | 2.33 | 0.12 |
| 25 | Irkutsk | 77,485 | 1790 | 247.4 | 0.15 | 0.021 | 0.37 | 75 | 2.01 | 0.28 |
| 26 | Chita | 43,236 | 2324.2 | 325.9 | 0.17 | 0.023 | 0.54 | 55 | 3.02 | 0.42 |
| 27 | Buryatiya | 35,169 | 1021.8 | 149.2 | 0.14 | 0.020 | 0.21 | 70 | 2.00 | 0.29 |
| 28 | Primorsk | 16,458 | 761.7 | 200 | 0.18 | 0.046 | 0.35 | 75 | 2.35 | 0.62 |
| 29 | Amursk | 36,181 | 1793.1 | 130.1 | 0.18 | 0.013 | 0.24 | 65 | 2.82 | 0.20 |
| | Total | 533,916 | 33,786 | 3022.8 | | | 5.04 | | | |
| | Mean | | | | 0.17 | 0.015 | | 75 | 2.22 | 0.20 |

**Table 6**
Comparison of mean annual erosion rates obtained from long-term monitoring observations at runoff plots and using the soil profile truncation method.

| The pair of nearby sites | Method | Location* | Period of observation | Mean erosion rate Mg $ha^{-1}$ $yr^{-1}$ | | References |
|---|---|---|---|---|---|---|
| | | | | Spring snow-melt | Rainstorm season | |
| 1 | Runoff plot | Chernigov Region, Ukraine | 1935–1969 | 3.2 | 2.1 | Gonchar (1981) |
| | Soil truncation** | Veduga Creek | 230 years | 3.3–3.5 | | This study |
| 2 | Runoff plot | Saratov region | 1973–1982 | 3.1 | 2.7 | Medvedev et al. (2016) |
| | | | 1983–2015 | 0.5 | 3.6 | |
| | Soil truncation** | Maly Kolyshley | 230 years | 7.8 | | This study |
| 3 | Runoff plot and rill measurements | Novosibirsk region | 1968–1979 | 8.1 | 17.1 | Khmelev. Tanasienko (1983) |
| | Soil truncation** | Pre-Salair Plain | 120 years | 9.0 | | Khmelev and Tanasienko (2009) |

* See Fig. 1 for location.
** Volumes were converted to mass using a standard bulk density of 1.2 t $m^{-3}$.

**Table 7**
Comparison of soil loss, calculated with the modified USLE and the soil truncation method for the regions of European Russia with Chernozems and Kastanozems.

| Region ndex* | Region | Area of arable land, $10^3$ ha A | Erosion volume**, $10^6$ m$^3$ $V_{USLE}$ | Erosion depth, m | | Ratio $\Delta h_{sp}/\Delta h_{USLE}$ |
|---|---|---|---|---|---|---|
| | | | | $\Delta h_{USLE}$ | $\Delta h_{sp}$*** | |
| 0 | Bashkiriya | 4778 | 1351.0 | 0.028 | 0.060 | 2.1 |
| 1 | Belgorod | 1652 | 2027.5 | 0.121 | 0.105 | 0.9 |
| 2 | Krasnodar | 4227 | 1484.1 | 0.033 | 0.030 | 0.9 |
| 3 | Kursk | 1969 | 1659.3 | 0.083 | 0.050 | 0.6 |
| 4 | Lipetsk | 1647 | 762.3 | 0.046 | 0.027 | 0.6 |
| 5 | Orel | 1660 | 1124.8 | 0.067 | 0.052 | 0.8 |
| 6 | Orenburg | 6287 | 964.0 | 0.014 | 0.058 | 4.2 |
| 7 | Penza | 2531 | 2217.8 | 0.088 | 0.056 | 0.6 |
| 8 | Rostov | 6043 | 1473.1 | 0.024 | 0.078 | 3.2 |
| 9 | Samara | 3090 | 792.4 | 0.026 | 0.047 | 1.8 |
| 10 | Saratov | 6359 | 1228.1 | 0.019 | 0.091 | 4.7 |
| 11 | Stavropol | 4258 | 2788.6 | 0.065 | 0.028 | 0.4 |
| 12 | Tambov | 2256 | 571.3 | 0.025 | 0.015 | 0.6 |
| 13 | Tatarstan | 3750 | 2689.3 | 0.072 | 0.056 | 0.8 |
| 14 | Tula | 1808 | 1937.3 | 0.107 | 0.046 | 0.4 |
| 15 | Uliyanovsk | 1808 | 777 | 0.013 | 0.039 | 2.9 |
| 16 | Volgograd | 5819 | 685.4 | 0.012 | 0.038 | 3.3 |
| 17 | Voronezh | 3159 | 1589.5 | 0.047 | 0.036 | 0.8 |

* See Fig. 2 for location.
** Calculated with the modified USLE from Table 1.8.1 in Soil Erosion in Europe, chapter.1.8 (tons were converted to m$^3$ using a soil density of 1.2 t m$^{-3}$) (Sidorchuk et al., 2006).
*** Values taken from Table 5.

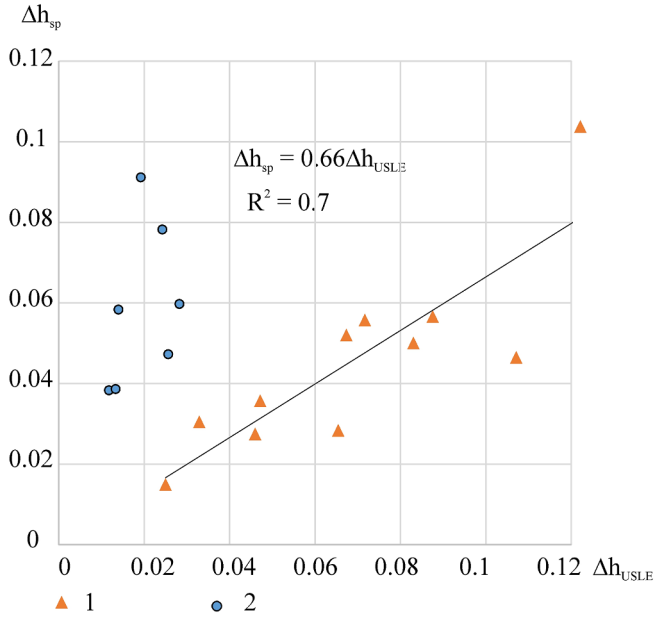


**Fig. 3.** Comparison of soil loss, calculated with the modified USLE ($\Delta h_{USLE}$) and the soil truncation method ($\Delta h_{sp}$) for the regions of European Russia with Chernozems–Kastanozems (see Table 7). 1 – regions, where ratio $\Delta h_{sp}/\Delta h_{USLE}$ is below 1; 2 – regions, where ratio $\Delta h_{sp}/\Delta h_{USLE}$ is more than 1.8 (highlighted in bold in Table 7).

Far East. The sources of this variability are well investigated and documented (Litvin et al., 2003): there are substantial differences in climatic conditions (snow thaw runoff and rainfall erosivity) and relief (*LS* factor and slope hollow density) characterising the arable land in question.

Using the soil profile truncation method allows evaluation of the combined losses of soil due to different soil degradation processes (water, wind, tillage erosion and soil losses with harvesting). The relative weights of each of these processes are different for different regions depending on the duration of cultivation, typical crop rotation used in the given region and wind erosion contributions. Their relative contributions, except in the case of wind erosion, to total soil losses for an individual field can be evaluated using the application of a combination of methods and techniques (Belyaev et al., 2005).

The total volume of soil, washed out from the 52.5 × 10$^6$ ha within EPR and from the 33.8 × 10$^6$ ha in Siberia and the Far East was estimated at 28.3 × 10$^9$ m$^3$ and 5.1 × 10$^9$ m$^3$, respectively. These values are more akin to gross, rather than net, soil loss since we were unable to include in our calculations the total sediment deposition within the arable fields. According to existing detailed studies in agricultural catchments, ~20–60% of eroded sediment is redeposited on cultivated slopes (Houben, 2008; Rommens et al., 2005; Walling and Collins, 2000, 2008; Golosov et al., 2011; Smetanová et al., 2017). Despite the above, our assessments of total soil loss for the period of intensive agriculture differ significantly from the latest calculations performed for all arable lands across different continents (Wang and van Oost, 2019). In our opinion, these latest independent estimates are gross overestimates in the case of Russia. Washed-out soil matter from cultivated land is delivered by permanent streams to fluvial networks, both natural and human-induced. The delivery ratio of this network is low and about 90% of eroded soil matter is deposited in the dry valley bottoms of those catchments with areas less than 100 km$^2$ (Sidorchuk, 2018). These deposits contain typical artefacts of the Anthropocene era, such as the pollen of cultural cereals and accompanying weeds, ceramics and glass, which can remain through geological time and be used as indicators of the impacts of human activity during the period of intensive agriculture. At the present time, the thickness of these deposits (sometimes called "legacy" sediments) in EPR and Siberia is about 1–2 m (Golosov et al., 1992; 2017, 2018b; Ryzhov and Kobylkin, 2011), and they form an organic carbon rich layer at the top of Quaternary deposits.

## 6. Conclusion

Estimates of total soil loss over large scales during the ploughing period have been calculated using the soil profile truncation method for three sentinel catchments and on a smaller scale for 29 regions of EPR and Siberia located in the steppe and forest-steppe zones. It has been established that the critical factors determining the differences in the rate of soil loss, both at the level of small catchments and at regional level, are the topography of arable slopes and the erosion index of precipitation. The duration of the ploughing period, which varies, on average, for the different regions of the Chernozems–Kastanozems belt of Russia, between 50 and 220 years, does not significantly affect the proportion of eroded land within the total area of arable land.

The rates of soil erosion obtained using the soil profile truncation method are in good agreement with the evaluation of soil erosion rates compiled during long-term monitoring of soil loss using runoff plots. The maximum soil erosion rates (mean value > 10 t ha$^{-1}$ yr$^{-1}$) during the period of intensive cultivation were identified in Rostov region, mainly because of both of water and wind soil erosion and in the Saratov region due to a dense network of hollows on the interfluves of the Privolzskaya upland in the western part and due to wind erosion in the flat eastern part. In Siberia, the highest gross soil loss rate (mean = 7.2 t ha$^{-1}$ yr$^{-1}$) is observed in Primorsky province, mainly because of the high amounts of heavy rainfall. The total volume of eroded soil during the period of ploughing in the Chernozems–Kastanozems belt of European Russia, Siberia and the Far East amounted to 28.3 × 10$^9$ m$^3$ and 5.1 × 10$^9$ m$^3$, respectively (excluding sediment re-deposition on the arable land). These values are significantly lower than the latest assessment (Wang and van Oost, 2019) for these territories, despite the fact that they include the total soil loss driven by water, wind and tillage erosion and additional losses during harvesting. The work presented herein shows how long-term

datasets can be used to assemble much needed information on soil erosion rates associated with intensive farming.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

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## References

Afonin, A.N, Green, S.L, Dzyubenko, N.I, Frolov, A.N., 2008. Agroecological atlas of Russia and neighboring countries: economically significant plants, their pests, diseases and weeds. http://www.agroatlas.ru.

Akça, E., Alba, S.D., Álvarez, A.G., Bialousz, S., Berger, B., Bielek, P., et al., 2005. Soil Atlas of Europe. European Soil Bureau Network, Luxembourg.

Arnalds, O., Barkarson, B.H., 2003. Soil erosion and land use policy in Iceland in relation to sheep grazing and government subsidies. Environ. Sci. Policy 6 (1), 105–113.

Bazhenova, O.I., Lyubtsova, E.M., Ryzhov, Yu.V., Makarov, S.A., 1997. Space-time analysis of the dynamics of erosion processes in the south of Eastern Siberia. Science, RAS, St. Petersburg.

Beach, T., 1994. The fate of eroded soil: sediment sinks and sediment budgets of agrarian landscapes in Southern Minnesota, 1851–1988. Ann. Assoc. Am. Geogr. 84, 5–28.

Belyaev, V.R., Wallbrink, P.J., Golosov, V.N., Murray, A.S., Sidorchuk, A.Y., 2005. A comparison of methods for evaluating soil redistribution in the severely eroded Stavropol region, southern European Russia. Geomorphology 65, 173–193.

Bezukhov, D.A., Entin, A.L., 2019. Probabilistic approach to forecasting the formation of ephemeral gully network within arable interfluves. Vestnik MGU. Series 5. Geography 6, 39–49.

Bork, H.-R., 1983. Die holozäne Relief- und Bodenentwicklung in Lößgebieten, Beispiele aus dem Untereichsfeld. Catena Suppl. 3, 1–93.

Ditzler, C., Scheffe, K., Monger, H.C., 2017. Soil Survey Manual (Agriculture Handbook N° 18). Unites States Department of Agriculture, Soil Science Division Staff, USA.

Dokuchaev, V.V., 1892. Our steppes before and now ('Nashi stepi prezhde i teper') St. E. Evdokimov print house, Petersburg.

Dotterweich, M., 2008. The history of soil erosion and fluvial deposits in small catchments of central Europe: Deciphering the long-term interaction between humans and the environment — a review. Geomorphology 101, 192–208.

Goleusov, P.V., Lisetskii, F.N., 2008. Soil development in anthropogenically disturbed forest-steppe landscapes. Eurasian Soil Sc. 41, 1480–1486.

Golosov, V., Belyaev, V., 2013. The history and assessment of effectiveness of soil erosion control measures deployed in Russia. Int. Soil Water Conserv. Res. 1 (2), 26–35.

Golosov, V.N., Gennadiev, A.N., Olson, K.R., Markelov, M.V., Zhidkin, A.P., Chendev, Y.G., Kovach, R.G., 2011. Spatial and temporal features of soil erosion in the forest-steppe zone of the East-European Plain. Eurasian Soil Sc. 44, 794–801.

Golosov, V., Yermolaev, O., Litvin, L., Chizhikova, N., Kiryukhina, Z., Safina, G., 2018a. Influence of climate and land use changes on recent trends of soil erosion rates within the Russian Plain. Land Degrad Dev 29 (8), 2658–2667.

Golosov, V.N., Ivanova, N.N., Gusarov, A.V., Sharifullin, A.G., 2017. Assessment of the trend of degradation of arable soils on the basis of data on the rate of stratozem development obtained with the use of $^{137}$Cs as a chronomarker. Eurasian Soil Sci. 50 (10), 1195–1208.

Golosov, V., Koiter, A., Ivanov, M., Maltsev, K., Gusarov, A., Sharifullin, A., Radchenko, I., 2018b. Assessment of soil erosion rate trends in two agricultural regions of European Russia for the last 60 years. J Soil. Sediment. 18 (12), 3388–3403.

Golosov, V.N., Ivanova, N.N., Litvin, L.F., Sidorchuk, A.Y., 1992. Sediment budget in river basins and small river aggradation. Geomorphologiya 4, 62–71.

Gonchar, A.I., Sribny, I.K., 1981. Evaluation of soil loss from slopes. Gidrokhimiya i Melioraciya 7, 28–30.

Gusarov, A.V., Golosov, V.N., Sharifullin, A.G., Gafurov, A.M., 2018. Contemporary trend in erosion of arable southern Chernozems (Haplic Chernozems Pachic) in the West of Orenburg Oblast (Russia). Eurasian Soil Sc. 51 (5), 561–575.

Fuchs, M., Will, M., Kunert, E., Kreutzer, S., Fischer, M., Reverman, R., 2011. The temporal and spatial quantification of Holocene sediment dynamics in a meso-scale catchment in northern Bavaria, Germany. The Holocene 21, 1093–1104.

Houben, P., 2008. Scale linkage and contingency of field-scale and hillslope-scale controls of long-term soil erosion: Anthropogeomorphic sediment flux in agricultural loess watersheds of Southern Germany. Geomorphology 101, 172–191.

Ivanova, N.N., Golosov, V.N., Zhokhova, A.V., Tishkina, E.V., 1998. Agrogenic transformation of the soil cover within a small catchment area (by the example of the forest-steppe part of the Oka-Don plain). Eurasian Soil Sci. 31, 197–204.

Ito, A., 2007. Simulated impacts of climate and land-cover change on soil erosion and implications for the carbon cycle, 1901 to 2100. Geophys. Res. Lett. 34, L09403. https://doi.org/10.1029/2007GL029342.

Khmelev, V.A., Tanasienko, A.A., 1983. Chernozems of the Kuznetsk kotlovina(Historical-evolutionary and genetic-production aspects). "Nauka", Novosibirsk.

Khmelev, V.A., Tanasienko, A.A., 2009. Land resources of Novosibirsk region and ways of their rational use. Izd-vo SO RAN, Novosibirsk.

Kolesnichenko, V.T., 2003. Winter Wheat Zalarinka in the Irkutsk region (the results of field experiments). Promekobezopasnost, Moscow.

Kozmenko, A.S., 1937. Fighting with soil erosion. Publishing house of the Academy of Agricultural Sciences, Moscow-Leningrad.

Krasilnikov, P., Makarov, O., Alyabina, I., Nachtergaele, F., 2016. Assessing soil degradation in northern Eurasia. Geoderma Regional 7, 1–10.

Kulik, V.V., Ratnikova, G.N., Shubich, S.M., Fateeva, T.V., 2007. The state (National) report on the condition and use of lands in the Russian Federation in 2006. Moscow, https://rosreestr.ru/site/activity/gosudarstvennyy-natsionalnyy-doklad-o-sostoyanii-i-ispolzovanii-zemel-rossiyskoy-federatsii/.

Kuznetsova, J.S., Belyaev, V.R., Markelov, M.V., Ivanova, N.N., 2007. Evaluation of spatial and temporal variability of soil redistribution processes within an arable slope (paper 2). Geomorfologiya 2, 60–69. https://doi.org/10.15356/0435-4281-2007-2-60-69.

Larionov, G.A., 1993. Water and wind erosion: main features and quantitative assessment. MGU Publ, Moscow.

Larionov, G.A., Skidmore, E.L., Kiryukhina, Z.P., 1997. Wind Erosion in Russia: Spreading and Quantitative Assessment. Kansas State University, Manhattan, KA, USA.

Lewis, D.T., Lepele, M.J., 1982. Quantification of soil loss and sediment produced from eroded land. Soil Sci. Soc. Am. J. 46, 369–372. https://doi.org/10.2136/sssaj1982.

Litvin, L.F., Kiryukhina, Z.P., Krasnov, S.F., Dobrovol'skaya, N.G., 2017. Dynamics of agricultural soil erosion in European Russia. Eurasian Soil Sc. 50 (11), 1344–1353.

Litvin, L.F., Zorina, Y.F., Sidorchuk, A.Y., Chernov, A.V., Golosov, V.N., 2003. Erosion and sedimentation on the Russian Plain, part 1: contemporary processes. Hydrol. Process. 17 (16), 3335–3346.

Lyuri, D.I., Goryachkin, S.V., Karavaeva, N.A., Denisenko, E.A., Nefedova, T.G., 2010. Dynamics of agricultural lands of Russia in XX century and post-agrogenic restoration of vegetation and soils. GEOS, Moscow.

Massalsky, V.I., 1897. The gullies of the Chernozems belt of Russia, their distribution, development and activity. St, Petersburg.

Medvedev, I.F., Levitskaya, N.G., Makarov, V.Z., Nazarov, V.A., 2016. The results of monitoring of erosion processes on Chernozems in the Volga region. Agrar. Nauch. Zhnaniya. 8, 29–34.

Morgan, R.P.C., 1996. Soil Erosion and Conservation, second ed. Harlow, Longman.

Nosin, V.A., Fedorin, Y.V., Friev, T.A., 1973. State Instruction on Soil Surveys and Compilation of Large-Scale Soil Land Use Maps. Kolos, Moscow.

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, C., 2015. The new assessment of soil loss by water erosion in Europe. Environ. Sci. Policy 54, 438–447.

Panagos, P., Borrelli, P., Meusburger, K., Yu, B., Klik, A., Lim, K.-J., Yang, J.-E., Ni, J., Miao, C., Chattopadhyay, N., Sadeghi, S.H., Hazbavi, Z., Zabihi, M., Larionov, G.A., Krasnov, S.F., Gorobets, A.V., Levi, Y., Erpul, G., Birkel, C., Hoyos, N., Naipal, V., Tarso, P.S.O., Bonilla, K.A., Meddi, M., Nel, W., Al Dashti, H., Boni, M., Diodato, N., Van Oost, K., Nearing, M., Ballabio, C., 2017. Global rainfall erosivity assessment based on high-temporal resolution rainfall records. Sci. Rep. 7 (1), 4175. https://doi.org/10.1038/s41598-017-04282-8.

Pugachev, V.S., 1984. In: Probability Theory and Mathematical Statistics for Engineers. Pergamon Press, Oxford. https://doi.org/10.1016/C2013-0-06054-9.

Reimche, V.V., 1986. Erosion processes in the forest-steppe landscapes of Transbaikalia (case study the Kuitunka river basin). Izd-vo Nauka, Novosibirsk.

Rommens, T., Verstraeten, G., Lang, A., Poesen, J., Govers, G., Van Rompaey, A., Lang, A., Peeters, I., 2005. Soil erosion and sediment deposition in the Belgian loess belt during the Holocene: establishing a sediment budget for a small agricultural catchment. Holocene 15, 1032–1043. https://doi.org/10.1191/0959683605hl876ra.

Rohatgi, V.K., 1976. An Introduction to Probability Theory and Mathematical Statistics. Wiley, New York. https://doi.org/10.1002/9781118165676.

Ryzhov, Y.V., 2015. Gullying in the South of Eastern Siberia. Geo, Novosibirsk.

Ryzhov, J.V., Kobylkin, D.V., 2011. XX Century development of erosion-accumulation processes in the small river catchment of the South-eastern Pribaikalye. Geomorphologiya 2, 42–48. https://doi.org/10.15356/0435-4281-2011-2-42-48.

Shoba, S.A., 2011. National Atlas of Soils of the Russian Federation. ASTREL Publishing House, Moscow, Russia.
Sidorchuk, A., 2018. The fluvial system on the East European plain: sediment source and sink. Geogr. Environ. Sustain. 11(3), 5–20. doi:10.24057/2071-9388-2018-11-3-05-20.
Sidorchuk, A.Y., Golosov, V.N., 2003. Erosion and sedimentation on the Russian Plain, II: the history of erosion and sedimentation during the period of intensive agriculture. Hydrol. Process. 17 (16), 3347–3358.
Sidorchuk, A., Litvin, L., Golosov, V., Chernysh, A., 2006. European Russia and Byelorus. In: Boardman, J., Poesen, J. (Eds.), Soil Erosion in Europe. John Wiley & Sons Ltd., Chishester, pp. 73–93.
da Silva, A.M., Alvares, C.A., Watanabe, C.H., 2011. Natural potential for erosion for Brazilian territory. In: Godone, D., Stanchi, S. (Eds.), Soil erosion studies. InTechOpen, Rijeka, pp. 3–24. https://doi.org/10.5772/1820.
Smetanová, A., Verstraeten, G., Notebaert, B., Dotterweich, M., Létal, A., 2017. Landform transformation and long-term sediment budget for a Chernozem-dominated lowland agricultural catchment. CATENA 157, 24–34.
Surinov, A.E., Baranov, E.F., Bezborodova, T.S., 2018. Russia in Numbers: A Brief Statistical Compilation. Rosstat, Moscow.
Świtoniak, M., 2014. Use of soil profile truncation to estimate influence of accelerated erosion on soil cover transformation in young morainic landscapes, North-Eastern Poland. CATENA 116, 173–184.
Sobolev, S.S., 1948. The development of erosion processes in the territory of the European part of the USSR and the fight against them, vol. 1, Publishing House of the Academy of Sciences of the USSR, Leningrad.
Sobolev, S.S., 1960. The development of erosion processes in the territory of the European part of the USSR and the fight against them, vol. 2, Publishing House of the Academy of Sciences of the USSR, Leningrad.
Stolbovoi, V., Fischer, G., 1998. A New Digital Georeferenced Database of Soil Degradation in Russia. In: Blume, H.P., Eger, H., Fleischhauer, E., Hebel, A., Reij, C., Steiner K.G. (Eds.), Towards Sustainable Land Use, vol. I. Catena Verlag, Reiskirchen, pp. 143–152.
The Combined State Register of Soil Resources of Russia, 2014. http://infosoil.ru/reestr.
Trimble, S.W., 1999. Decreased rates of alluvial sediment storage in the Coon Creek Basin, Wisconsin, 1975–93. Science. 285, 1244–1246.
Tsvetkov, M.A., 1957. Changes in the forest cover of European Russia from the end of the 17th century to 1914. Publishing House of the Academy of Sciences of the USSR, Moscow.
United States Soil Conservation Service, 1980. Gross erosion and sediment yield, Flat Bayou, portion of the Plum Bayou Watershed, Jefferson County, Arkansas. USDA-SCS, Fort Worth, Tex. Map. https://www.loc.gov/item/85693533/.
United States Soil Conservation Service 1934. Reconnaissance erosion survey of the State of North Carolina. [S.l, 1934] Map. https://www.loc.gov/item/99446155/.
van Hooff, P.P.M., Jungerius, P.D., 1984. Sediment source and storage in small watersheds on the Keuper marls in Luxembourg. CATENA 11, 133–144.
Vandaele, K., Poesen, J., 1996. Spatial and temporal patterns of soil erosion rates in an agricultural catchment, central Belgium. Catena 25, 213–226.
Van Oost, K., Quine, T.A., Govers, G., De Gryze, S., Six, J., Harden, J.W., Ritchie, J.C., McCarty, G.W., Heckrath, G., Kosmas, C., Giraldez, J.V., da Silva, J.R.M., Merckx, R., 2007. The impact of agricultural soil erosion on the global carbon cycle. Science 318 (5850), 626–629.
Van Oost, K., Van Muysen, W., Govers, G., Deckers, J., Quine, T.A., 2005. From water to tillage erosion dominated landform evolution. Geomorphology 72 (1-4), 193–203.
Vodarskiy, Ya.E., 1988. Nobility land tenure in Russia in the XVII-first half of the XIX century: size and location. USSR Academy of Sciences Publ, Moscow.
Volkov, S.N., 1988. Materials of generalization of the general schemes of anti-erosion measures. Roszemproekt, Moscow.
Walling, D.E., Collins, A.L., 2000. Integrated assessment of catchment suspended sediment budgets: A technical manual. Univ, Exeter, Exeter.
Walling, D.E., Collins, A.L., 2008. The catchment sediment budget as a management tool. Environ. Sci. Policy 11, 136–143.
Wang, Zhengang, Van Oost, Kristof, 2019. Modeling global anthropogenic erosion in the Holocene. The Holocene 29 (3), 367–379.
Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses. Agric. Handbook 537. Washington D.C.: U.S. Dept. Agric.
www.meteo.ru.